(NASA-CR-161316) [ENERGY TRANSPORT THROUGH THE SOLAR ATMOSPHERE] Final Technical Report (Solar Physics Research Corp.) 38 p HC A03/MF A01 CSCL 03B

N79-34141

Unclas

G3/92 35984

Contractor: Solar Physics Research Corporation
4720 Calle Desecada
Tucson, Arizona 85718

Title: Technical Report, Final Report

Date: August 31, 1979

Contract: NAS8-33104

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Abstract. Disk center observations of intensity and velocity fluctuations measured with the 523.3 and 525.0 nm Fe I lines have been compared with simultaneous measurements of intensity fluctuations of the 4613.55 nm CO line formed in the temperature minimum, the Lyα and a C II line formed in the middle chromosphere, C III, O IV and O VI formed in the transition region, and a Mg X line formed in the corona.

Strong fluctuations in the 3-5 mHz range are observed from the photosphere to the middle chromosphere. In the transition region and corona, intensity fluctuations do not exhibit specific periods. The propagation of these intensity fluctuations, studied by three techniques, is found to be upward in the photosphere and temperature minimum and upward from the middle chromosphere to the transition region at near sonic speeds. We do not find a clear indication of propagation direction between the temperature minimum and middle chromosphere. There is a weak suggestion of downward propagation in this region.

Specific intensity pulses in the transition region cannot be associated with specific intensity or velocity events in the photosphere. We suggest that a major change in the mode of wave propagation occurs above the temperature minimum.

1. Introduction

One of the central problems in solar physics is the source of energy to heat the chromosphere and the corona. An essential aspect of this problem is the study of energy transport through the solar atmosphere. One obvious candidate for propagating energy to the upper levels of the solar atmosphere is by wave motion. Results of both recent theoretical and observational studies of wave propagation in and the heating of the solar atmosphere have been frequently reviewed (e.g, Stein and Leibacher, 1974; Beckers and Canfield, 1976; Canfield and Beckers, 1976; White, 1976; Cram, 1977; Deubner, 1977, 1979; Jordan, 1977a, b; Mein, 1979).

The source of the waves which may propagate energy to the upper levels of the atmosphere is thought to be the photospheric short-period ($\sim$5 min and shorter) oscillations. Observations have shown that there is sufficient energy in the oscillations at the photospheric level to heat the chromosphere and the corona. But to actually heat the higher levels in the solar atmosphere requires a net upward propagation of wave energy and a suitable dissipation mechanism at the appropriate heights.

The source of photospheric oscillations with periods around 5 min has been clearly identified with non-radial p-mode (acoustic) waves trapped in a cavity beneath the photosphere (cf. Deubner, 1975; Ando and Osaki, 1975; Ulrich and Rhodes, 1977; Rhodes _et al_., 1977a, b). Waves in the visible layers

of the photosphere, which are excited by leakage of the subphotospheric oscillations, are identified as mainly evanescent in the frequency range below 5 mHz and upward propagating acoustic at higher frequencies (cf. Deubner, 1974; Schmieder, 1976, 1977, 1979; Lites and Chipman, 1979).

Careful studies of the phase lags of photospheric oscillations at various heights indicate that significant amounts of energy are propagated upward by waves (Canfield and Musman, 1973; Schmieder, 1976; Cram, 1978; Lites and Chipman, 1979). The energy flux at photospheric levels in waves of frequencies less than 10 mHz has been determined to be about 10^7 erg cm^2 s^{-1} which is sufficient to heat the atmosphere above. However, most of this energy appears to be radiatively dissipated low in the atmosphere (Schmieder, 1977, 1979) so that by a height of about 1000 km above the photosphere the energy flux in waves is of the order of 10^4 erg cm^2 s^{-1} which is 1 - 2 orders of magnitude too small to heat the overlying atmosphere (Athay and White, 1977, 1978; Lites and Chipman, 1979).

Most observational and theoretical work on the 5 min oscillations below the temperature minimum region seems to be in good accord. Above this level, the present situation is confusing because of the changing nature of wave propagation and dissipation, and conflicting observational and theoretical results. We expect that a cavity is formed between the temperature minimum and the transition region (e.g. Stein and Leibacher, 1974). Waves which enter this cavity from

below might be expected to be reflected and otherwise mixed (Wentzel, 1978). At this height, dissipation by shock waves is likely to be important (e.g., Ulmschneider et al., 1978).

Observational studies of the chromosphere at frequencies $<$10 mHz show either little or no wave propagation (e.g. Mein, 1978; Schmieder, 1979) or upward propagation (e.g. Cram, 1978; Lites and Chipman, 1979) or downward propagation, especially near the transition region (Chipman, 1978). As Deubner (1979) points out, no chromospheric observations have been made which meet all the requirements to unambiguously sort out which wave modes are significant in the chromosphere.

In the transition region and corona, the periodic oscillations so easily detected at lower levels of the atmosphere are not well defined. Intensity fluctuations at these higher levels are usually characterized as aperiodic pulses. Some analyses do not reveal evidence for enhanced oscillations at periods around 300 s (e.g. Vernazza et al., 1975; Artzner et al., 1978; Bruner, 1978) while others do (e.g. Chapman et al., 1972; Bruner et al., 1976; Tsubaki, 1977; Chipman, 1977, 1978; Athay and White, 1979). Both upward and downward propagation of these waves have been reported. The energy in wave motions in the transition zone has been estimated by various means (Bruner, 1978; Athay and White, 1979; Bruner and McWhirter, 1979) and is found to be inadequate as a source of heating if the mode is primarily acoustic.

Previous observational investigations have studied the association of intensity fluctuations between the photosphere

and chromosphere or between the temperature minimum and the transition region but none to our knowledge has attempted to study fluctuations from the photosphere through the temperature minimum, chromosphere and transition region to the corona simultaneously.

In this paper we report on a study of simultaneous observations from the photosphere to the corona at the solar disk center. The investigation was aimed at defining the time relations between fluctuations from the photosphere to the corona with particular emphasis on the possible association of aperiodic brightenings high in the atmosphere with specific events in the photosphere.

2. Observations and Reduction

2.1. OBSERVATIONS

Observations from three instruments were used for this study. Coordination of the simultaneous observations on 17 September 1973 was done by D. Hall, J. Harvey, and R. Noyes. Photospheric observations were made by J. Harvey with the 40-channel magnetograph (Livingston et al., 1971) fed by the main image of the McMath telescope at Kitt Peak National Observatory. Twenty spatial elements of size 1.7 by 2.4 arc seconds were aligned along heliocentric position angle +185° for the first of two observing runs. For the second run, the elements were aligned along position angle +95°. For both runs, the tenth spatial element was kept coincident with the disk center to about 1 arc second. The magnetograph was operated in a Doppler

mode in which the sums and differences of the intensities in the red and blue wings of the Fe I spectrum lines at 523.3 and 525.0 nm were measured simultaneously for integration periods of 8.14 s. For both observing runs, 500 samples were recorded. The sky was clear and the seeing quality was about 2 arc seconds.

Observations of intensity fluctuations in the temperature minimum region of the upper photosphere were made by R. Allen and D. Hall with an infrared spectrometer fed by the west auxilliary telescope of the McMath telescope (Allen, 1978). The spectrometer isolated the 6.61355 μm CO line and spatial scans along heliocentric position angle +80° were made every 6.309 s by rotating a block of CaF_2 in front of the entrance aperture in size 0.9 by 2.9 arc seconds. The center of the scan was kept coincident with the solar disk center.

Observations of intensity fluctuations of six spectrum lines formed in the chromosphere, transition region and corona were made with the S-055 Extreme Ultraviolet (EUV) Spectrometer on board Skylab (Reeves <u>et al</u>., 1977). The entrance aperture of size 5 arc seconds square was scanned in heliocentric position angle +90° every 5.5 s. The center of the scan coincided with the solar disk center. Two runs were available. The first was terminated by a change in pointing and the second by sunset.

Supporting observations included raster scans near the disk center made with the EUV Spectrometer on Skylab, a full disk magnetogram, and Ca II 393.3 nm and He II 30.4 full disk spectroheliograms. A ledger of the observations is contained in Table I

TABLE I

Ledger of Observations on September 17, 1973

Observation	Time (UT)	Rate (s)	Spatial Element (arc sec)
Photospheric Velocity and Intensity			
Run 1	16:16:00 - 17:23:55	8.150	1.7 x 2.4
Run 2	17:44:00 - 18:51:44	8.128	1.7 x 2.4
CO Intensity			
Run 1	16:44:05 - 17:06:57	6.3086	0.9 x 2.9
Run 2	17:11:31 - 20:03:13	6.3086	0.9 x 2.9
Chromosphere, Transition Region and Corona Intensity			
Run 1	16:47:35.5-17:03:10.5	5.500	5.0 x 5.0
Run 2	18:15:48.3-18:43:18.3	5.500	5.0 x 5.0
Support Observations			
He II spectroheliogram	10:16		
Skylab raster 1	16:34:09		
Skylab raster 2	17:51:02		
Magnetogram	19:05:04		
Ca II spectroheliogram	20:04		

2.2. REDUCTION

Preliminary data reduction started with corrections to the photospheric observations for very low frequency time changes. The diurnal change in line-of-sight velocity due to the earth's rotation and a slow spectrograph drift were determined and removed from the velocity data. Variations in the transmission of the earth's atmosphere were determined by averaging the intensity signal over all spatial elements during a given time integration period and then using this average to normalize the intensities measured at each spatial element.

The same intensity correction procedure was applied to the CO line data after first correcting for a drift in the zero level of the infrared detector. This drift was easy to determine since a portion of each spatial scan blocked any light from entering the instrument. While corrections for scattered light within the Kitt Peak spectrometers (both operated in single pass) should be made, the data to determine the magnitude of such corrections are not available. The result is that both the photospheric and CO line intensity fluctuations are reduced in value probably by about 5%.

The next step consisted of extracting from each data set a single time series corresponding to the center of the solar disk. In this process, data from several spatial positions were combined to more closely match the coarse spatial aperture of the EUV spectrometer. Specifically, two of the photospheric observations were combined to produce a spatial element of 1.7 x 4.8 arc seconds and three of the CO line observations

were combined to produce a spatial element of 2.9 x 2.3 arc seconds. Atmospheric seeing and guiding jitter combine to effectively enlarge these values by 1 to 2 arc seconds.

After extracting the appropriate spatial element time series from each data set, the various data series were put on a common time scale. This was done by selecting start and end times for each of the EUV spectrometer observing runs as they were the shortest of all the runs. The total time interval of each run was divided into periods of about 1 s so that the number of points in each observing run was an integer power of 2. The various data sets were then interpolated onto a common time scale using the data reduction program REDUCER developed by J. Brault (Brault and White, 1971). Table II gives the final time periods analyzed and Figure 1 shows smoothed recordings of the intensity fluctuations of run 2.

TABLE II

Time Intervals Common to All Data Sets

Run	Start Time (s after 1600 UT)	Duration (s)	Number of Interpolated Points
1	2870.0	912.1068	1024
2	8163.0	1616.3112	2048

The accuracy of coalignment of the data sets was assessed as follows: the full disk magnetogram, Ca II and He II images were made to a common size and the position of the disk center assigned as that point equidistant from opposite limbs in all

position angles. A standard, equartorial, synodic rotation rate was used to shift the disk centers from one time to another. The structural features visible on the full disk observations were then located on the EUV spectrometer raster scans and the disk center transferred to these scans. The one-dimensional EUV scan position was then located on the EUV raster scans and it was determined that the center of the disk was within one resolution element ($\pm$5 arc seconds) of its expected position. We assumed that the ground based observations were centered on the disk center within one of their resolution elements as great care was taken during the observations to ensure this. Thus, we feel that the selected data sets are spatially coincident to $\pm$5 arc seconds.

The two observing runs were centered on opposite edges of an average chromospheric bright mottle comprising part of a quiet network of mixed magnetic polarity. Solar rotation carried the mottle accross the disk center during the time between the two observing runs.

3. Analysis and Results

In order to study the vertical propagation of fluctuations in the data set we first consider the height of formation of the nine spectrum lines and then apply three techniques to determine time delays of fluctuations at various heights.

3.3. HEIGHTS OF FORMATION OF THE OBSERVED SPECTRUM LINES

Throughout this paper we refer to five regions of the solar

atmosphere in which the investigated spectral lines are thought to be formed. These are: the photosphere, the Fe I lines at 525.0 and 523.3 nm; the temperature minimum, the CO line at 4613.55 nm; the upper chromosphere, Lyα - H I (121.6 nm) and C II (133.6 nm) lines; the transition region, C III (97.7 nm), O IV (55.3 nm), O VI (103.2 nm); and the corona, the Mg X (62.5 nm) line.

However, the interpretation of the intensity and velocity fluctuations and their propagation through the solar atmosphere requires a more specific determination of the height of formation of each of the lines. The calculation of the height of formation of spectrum lines relies on models of the solar atmosphere, which at least in the upper chromosphere, transition region and corona are approximations to the highly inhomogeneous atmospheric structure in these regions. The lines, of course, are not formed at one specific height in the atmosphere, but rather over a range of heights and temperatures. The EUV lines used in this study are formed over a much larger height and temperature range than the three lowest lines.

The heights of formation of the nine spectrum lines considered in this study were compiled from the literature based in part on models of the photosphere and chromosphere (Gingerich <u>et</u> <u>al</u>., 1971; Vernazza <u>et</u> <u>al</u>., 1973), and the transition region and corona (Gabriel, 1976) and on measures of the temperature of the observed lines and heights either measured or calculated on the basis of model atmospheres. Table III summarizes the values used in this study of temper-

TABLE III

Heights of Formation of Spectrum Lines Studied

Region	Element	Wavelength (nm)	T_e (10^3 K)	Reference	Height (km$^+$)	Reference
Photosphere	Fe I	525.0	5.7	1	60	3
	Fe I	523.3	5.0	1	175	3, 4
Temperature minimum	CO	4613.55	4.2	1, 2	420	1, 2
Upper Chromosphere	H I (Lyα)	121.6		5, 6	2300-2400	6, 7
			25	8		
	C II	133.6	20	5	2300	6, 7
			25	9, 10		
			40	11		
Transition region	C III	97.7	70	5	2400	12
			30	13	2300-3900**	10
			56	10		
	O IV	55.3	150	5	2400	12
			125	14		
	O VI	103.2	350	5	2450	12
			290	10	2100**	10
			310	11		
			330	15		
Corona	Mg X	62.5	1400	5	10600*	11
			1600	11	11000	16
			1200	10		

+ assumes the height scale of the HSRA (1)
* assumes Ly continuum is at 2000 km
**height above the visible limb

TABLE III - page 2

references

1 Gingerich *et al*. (1971)
2 Noyes and Hall (1972)
3 Giovanelli et al. (1978)
4 Lites (1972)
5 Reeves *et al*. (1974) and Vernazza *et al*. (1975)
6 Vernazza *et al*. (1973)
7 Chipman (1978)
8 Artzner *et al*. (1978)
9 Burton *et al*. (1971)
10 Burton *et al*. (1973)
11 Simon and Noyes (1972)
12 Gabriel (1976)
13 Loulergue and Nussbaumer (1977)
14 Jordan (1969)
15 Dupree and Goldberg (1969)
16 Simon (1972)

atures and heights of formation of the nine spectrum lines.

3.2. RELATION OF FLUCTUATIONS AT DIFFERENT HEIGHTS

Unless the fluctuations observed at various heights are very similar to each other, the associations between different heights can become ambiguous. We used three different techniques to try to remove such ambiguities.

3.2.1. Fourier Analysis

The Fourier transform of each time series was computed using standard techniques (Brault and White, 1971). The resulting amplitudes of the fluctuations as functions of frequency are shown in Figure 2. Because of the relatively short durations of the observing runs (15 and 30 min), the amplitudes at frequencies less than 2 mHz are not significant.

As expected, significant fluctuations are present in the 3-5 mHz range in many of the spectra. This frequency range is particularly prominent in the photosphere and temperature minimum lines but is also obvious in the Lyα and C II lines formed in the middle chromosphere. The transition zone lines do not show obvious peaks in the 3-5 mHz frequency range but rather a gradual rise of fluctuation amplitude to lower frequencies. An exception is the C III line observed during run 2 which shows a significant peak in the 3-5 mHz range. The coronal line similarly shows a peak during the second run.

We find no evidence for strong fluctuations in the 5-6 mHz range which have frequently been seen in chromospheric observations (e.g. Orrall, 1966; Elliot, 1969; Bhatnagar and

Tanaka, 1972; Simon and Shimabukuro, 1971; Deubner, 1974; Wefer, 1975; Chipman et al., 1976).

The amplitude spectra present a picture of strong oscillations in the 3-5 mHz range in the photosphere and temperature minimum regions which gradually become less dominant higher in the chromosphere, transition region and corona. The spectra vary considerably between the two runs which suggests significant time or space dependence of the nature of the fluctuations.

If we subtract the phases of the Fourier transforms of two time-series measurements, we obtain a phase difference spectrum. This was done for both observing runs using the 525.0 nm intensity and 523.3 nm velocity transforms as references. Figure 3 shows an example of a phase difference spectrum in which we have plotted phase differences over a total range of two cycles in order to reveal possible trends with frequency more clearly. This also emphasizes that ambiguities of integer cycles of phase difference are always possible with this type of analysis. The plot also shows a large amount of scatter which is typical of differences between the lower three lines and the higher six lines. The phase difference spectra are significant only for frequencies at which both fluctuations have significant amplitudes. To indicate this, the size of the symbols is proportional to the log of the product of the amplitudes of the two fluctuations (cross-power). Significant cross-power is present only below 6 mHz. We could not distinguish significant frequency trends

except among the photospheric and temperature minimum lines. Accordingly, we computed mean phase differences in the two frequency ranges centered at 3.3 and 5.5 mHz. More weight was given to the longer run 2 and errors were estimated from the variance in the values at each of the two frequencies. This procedure was done separately using photospheric intensity and velocity recordings as references. The results were then converted to time lags and shifted to zero time lag for the 525.0 nm intensity fluctuation and final results are given in Table IV.

3.2.2. Cross-Correlation Analysis

Because of the integer cycle ambiguity inherent in the phase spectrum analysis and because the intensity fluctuations in the transition region are more aperiodic than periodic, the phase difference spectrum analysis is not necessarily appropriate. As an alternative means of determining time lags of intensity fluctuations at various heights we computed cross-correlations of the various data sets with reference photospheric brightness and velocity recordings. The cross-correlations were computed by reversing the time axis of one of the two records to be cross-correlated and computing the Fourier transform of each record. The resulting (complex) Fourier transforms were multiplied together and then inverse transformed to yield the (real) cross-correlation of the two functions. An example of such a cross-correlation is given in Figure 4.

Typically the cross-correlation functions show maximum positive correlation of high-level intensity fluctuations in advance of the occurrence of fluctuations in the photosphere

TABLE IV

Time Delays (s) of Fluctuations in Various Spectrum Lines

Line nm		Fluctu-ation[2]	Analysis Technique: Phase Spectrum[1] 3.3 mHz	Phase Spectrum[1] 5.5 mHz	Cross-Correlation Run 1	Cross-Correlation Run 2	Continuity Analysis Run 1	Continuity Analysis Run 2
525.0	Fe I	B	0	0	0	0	0	0
525.0	Fe I	V	67 ± 3	0 ± 4	59 ± 5	60 ± 5	76 ± 25	38 ± 30
523.3	Fe I	B	34 ± 20	22 ± 2	17 ± 20	15 ± 10	2 ± 7	0 ± 14
523.3	Fe I	V	75 ± 11	50 ± 15	71 ± 10	63 ± 5	106 ± 30	45 ± 30
4613.6	CO	B	55 ± 5	48 ± 2	23 ± 10	49 ± 5	84 ± 32	55 ± 35
121.6	H I	B	-15 ± 5	-25 ± 7	56 ± 20	-29 ± 5	238 ± 45	185 ± 50
133.6	C II	B	-25 ± 10	-32 ± 10	-	-45 ± 10	278 ± 22	197 ± 70
97.7	C III	B	-24 ± 11	-45 ± 10	-	-37 ± 10	272 ± 45	213 ± 83
55.3	O IV	B	-28 ± 12	-60 ± 7	-	-29 ± 5	265 ± 42	230 ± 60
103.2	O VI	B	4 ± 18	-82 ± 5	-	1 ± 20	292 ± 38	279 ± 47
62.5	Mg X	B	-15 ± 8	-38 ± 7	-	-30 ± 20	541[3]	290 ± 15 509 ± 17
121.6	H I	D	135 ± 5	65 ± 7	175 ± 30	109 ± 5	195[3]	146 ± 60
133.6	C II	D	125 ± 10	58 ± 10	150 ± 15	92 ± 20	185[3]	152 ± 60
97.7	C III	D	126 ± 11	45 ± 10	70 ± 15	98 ± 15	220[3]	148 ± 80
55.3	O IV	D	122 ± 12	30 ± 7	100 ± 15	120 ± 20	-	161 ± 60
103.2	O VI	D	154 ± 18	8 ± 5	-	155 ± 20	-	163 ± 60
62.5	Mg X	D	135 ± 8	52 ± 7	-	115 ± 20	-	190 ± 60 367 ± 50

(1) weighted mean of runs 1 and 2
(2) B = brightening; V = upward velocity; D = darkening
(3) one event only

A strong negative cross-correlation at high levels usually follows photospheric fluctuations. We measured the time lags associated with maximum positive and negative cross-correlations using both photospheric intensity and velocity records as references. The time lags were then shifted to a common scale of zero time lag for 525.0 nm brightenings and the mean results and estimated errors are given in Table IV. Run 1 was too short to give meaningful results in many cases.

3.2.3. Continuity Analysis

Our cross-correlation analysis is limited by the short length of the records, possible dominance of the results by one large event and by an implicit assumption in the analysis that the data strings repeat cyclically beyond the ends of the recorded data. There is also the possibility of a change in shape of intensity event time profiles at different heights which would distort the phase difference spectrum and cross-correlation analyses. We attempted to circumvent these problems by making plots, such as Figure 1, showing the intensity fluctuations in an ascending height sequence. With a great deal of subjectivity, it is possible to identify events at one level which appear to be continuous with events at adjacent levels after a suitable time shift and it is this we use in an attempt to trace individual brightness fluctuations from the photosphere to the corona. This process, however, is difficult for two reasons: (1) the radical change in the

character of the intensity variations from the photosphere to the transition region - coronal levels, and (2) the lack of observations between the temperature minimum (CO line) and the upper chromosphere (Lyα and C II lines).

The intensity variations with time of each spectral line are shown in Figure 1 (run 2) and are arranged in order of increasing height as specified in Table III. In the lower atmospheric levels (photosphere) fairly periodic 5 min intensity oscillations are seen. But in the progression to the higher atmospheric lines we find, as we did in the amplitude spectra, little periodicity in the intensity fluctuations. Individual intensity pulses, however, can be followed from one line to the next, and it is this identification we use in attempting to trace photospheric fluctuations into the higher atmosphere.

The propagation trends of individual intensity fluctuations (both bright and dark) have been determined in the higher six spectral lines and compared with the propagation trends observed in the photospheric lines. The intensity fluctuations in the photosphere, with one exception, showed an upward propagation of the disturbances from the Fe I to CO lines as was also found in the phase difference and cross-correlation analyses. In the six highest lines (Lyα to Mg X), we infer both upward and downward propagation of bright and dark intensity fluctuations based on the timing of individual intensity fluctuations with height. The net propagation, however, in the higher lines appears to be upward.

The lack of observations of the intensity fluctuations over most of the chromospheric region prevents us from making an unambiguous match between the intensity fluctuations in the photosphere and those observed in the C II and H I lines, formed in the upper chromosphere. Based on the generally upward propagating intensity fluctuations both in the photosphere and transition region, if we assume that the intensity oscillations originating in the photosphere continue to propagate upward into the transition region as either dark or bright intensity pulses, a fit between the intensity variations in the lower and higher spectral lines can be made. The results of such a fit are listed in Table IV, along with variations in the time lags for each spectral line found among the 15 intensity fluctuations followed.

The intensity pulses in the higher regions of the atmosphere identified in this way with photospheric oscillations were found to lag about 150 s (for a dark event association) to about 200-250 s (for a bright event association). These results do not agree very well with the time lags deduced from the phase difference spectra or cross-correlation analyses.

4. Discussion

The observational results of this investigation are indicated in Figure 5 and may be interpreted in several ways. However, a key feature of this study is the restricted amount of data available which causes considerable uncertainty about how

typical are our results. In particular, run 1 is simply too short in duration to lead to significant conclusions and we concentrate our discussion on the nearly 30 min long run 2.

The photospheric spectrum lines used for this study give results which are consistent when analyzed by three different techniques and which agree with the results of earlier studies. We find that most of the fluctuation in intensity and velocity falls in the frequency range 3-5 mHz and that, in a given spectrum line, upward velocity maxima lag behind brightness maxima by 50-60 s. The increasing lag of brightness fluctuations at increasing heights which we observe is consistent with disturbances propagating upward with a speed comparable to the local sound speed. None of these results are new.

The six spectrum lines formed in the upper chromosphere, transition region and corona show significant intensity fluctuations in the 3-5 mHz range and the Ly α, C II, C III and Mg X lines even show local maxima in this frequency range. This result is contrary to the findings of Vernazza et al. (1975), Artzner et al. (1978) and Bruner (1978) but is similar to the results of Athay and White (1977, 1979) and Chipman (1978). The explanation for the discrepancies of these various results is probably the one advanced by Athay and White (1979): first, oscillations with periods around 300 s in the transition zone are not present all the time at all places and, second, the coherence time for such oscillations

is short. The result is that whether or not a significant peak in intensity fluctuations appears in a spectral analysis at frequencies around 3-5 mHz depends on the duration of the data sequence and on the particular time and location of the observation.

Vernazza et al. (1975) found evidence from a cross-correlation analysis for time lags between high- and low-excitation, line-intensity fluctuations in the chromosphere and transition region in the sense that O VI fluctuations followed C II fluctuations by roughly 17 s. Lyα fluctuations were anomalously late but other line pairs gave consistent results. Our cross-correlation analysis gives results which are consistent with Vernazza et al., within the limits of the errors associated with our much smaller data set. Our results also show Lyα fluctuations to be anomalously late. The continuity analysis indicates that both bright and dark fluctuations are consistent with an upward propagating disturbance at the rate suggested by the results of Vernazza et al. (1975). The phase difference analysis gives discordant results at 3.3 and 5.5 mHz. The former frequency indicates no particular upward or downward propagation although the results are consistent with the upward propagation found by Vernazza et al. (1975). However, the 5.5 mHz results suggest a downward propagation contrary to all the other evidence. We believe this result is spurious owing to the relatively small amount of fluctuation amplitude in most of the spectrum lines at this frequency.

Results for the Mg X coronal line cannot be interpreted as a continuation of the transition region disturbance upward for another 8000 km at a sonic or near sonic speed. Formally, our results indicate that intensity fluctuations in the Mg X line occur virtually at the same time as fluctuations in the transition region. The implication is that the height of formation we used is not correct (and Mg X is largely formed within the height range of the transition region) or that the nature of intensity fluctuation propagation changes radically above the transition region (change to evanescent mode) or that our result is spurious due to the small data sample. We do not know which, if any, of these interpretations is correct.

There is a height gap of almost 2000 km between the CO line and the low excitation transition region lines used in our study. This gap makes is difficult to join the ground-based and space observations. We did not presume that brightenings in the photosphere were necessarily associated with brightenings in the chromosphere and transition region. Our analyses also admitted the possibility of darkenings at higher altitudes. Previous analyses have compared brightness fluctuations in the temperature minimum (comparable with our CO observations) with lines of Fe II and Si II formed in the low chromosphere (Chipman, 1978) and transition region lines due to C II, Si IV and C IV (Chipman, 1978; Athay and White, 1979). Our results from phase difference and cross-

correlation analyses are similar to Chipman's result that intensity fluctuations in the transition region appear to lead fluctuations in the temperature minimum region. However, as Athay and White (1979) point out, the delay expected for a disturbance to travel from the temperature minimum to the transition region at the sound speed is of the order of 300 s - about the same as the time between successive fluctuations. Therefore, from phase difference analyses alone there will be ambiguities of one cycle unless the data are precise enough to establish in detail the phase shift as a function of frequency with good frequency resolution. Our data do not permit this to be done.

In order to resolve the one cycle ambiguity, we turn to the cross-correlation analysis. Presumably if there is a delay of at least one cycle between transition region fluctuations and those in the temperature minimum, the maximum cross-correlation will indicate the shift of one cycle. Unfortunately, the peak positive cross-correlation of transition region fluctuations with photospheric fluctuations after one cycle is considerably smaller. If we attempt to associate individual events in the two layers (continuity analysis) then we find the best correlation between brightenings in the transition region and those in the temperature minimum occur after about 150 s. The reason this result is different from the cross-correlation result is the greater weight placed on small events with the continuity analysis and the lack with this analysis of an assumption that the data repeat period-

ically beyond the ends of the recorded data string, as is required with the cross-correlation analysis.

There seems to be no obvious way to distinguish whether brightenings in the photosphere are associated with brightenings or darkening in the transition region on the basis of our data. The cross-correlations are generally equally strong for brightenings and darkenings (e.g. Figure 4). Nor can we unambiguously identify the same event at the two height levels in order to solve the problem.

Several alternative conclusions seem to be consistent with the available data. First, if we assume that a brightening continues upward between the temperature minimum and the transition region at roughly the sound speed, then we expect a time delay of the order of 280 s. This value is marginally consistent with the results of our phase difference analysis at 3.3 mHz if we add one cycle to the time delays. If the time delay were reduced to 180 s then all of our results (except the 5.5 mHz phase analysis) would be consistent but this requires a propagation speed of the order of 11 km s^{-1} through the chromosphere, somewhat supersonic. We note that Athay and White (1979) found evidence for a time delay between the temperature minimum and the transition zone of typically 300 s but at least one event with a time delay of only 150 s. In view of uncertainties in the atmospheric structure at different points in the chromosphere, we feel that one justifiable interpretation of our results is upward propagation of brightenings at speeds near the sound

speed.

A second interpretation is that photospheric brightenings are associated with transition region darkenings. A recent study by Poletto (1979) shows that weak shocks propagating through the transition region will produce line intensity weakenings rather than the brightenings associated with stronger shocks. The time delay between the temperature minimum brightenings and the transition region darkenings is about 75 s by all the analysis techniques (except the 5.5 mHz phase difference analysis). If we add one cycle to the fluctuations in the transition region then a subsonic propagation speed results (~ 5 km s^{-1}) but this addition is not at all justified by the cross-correlation results.

A third interpretation of our results is that the apparent correlations between photospheric and transition region fluctuations are mainly spurious and merely the result of the coincidence that both levels show significant fluctuations in the 3-5 mHz range. According to present ideas, the photospheric oscillations are caused by leakage in the form of evanescent waves of standing acoustic waves trapped in a subphotospheric cavity. The evanescent waves propagate energy upward by "tunneling" through the temperature minimum to a chromospheric cavity in which acoustic waves in the 3-5 mHz range may propagate. The nature of wave propagation in the chromospheric cavity (between the temperature minimum and the transition region) is not yet clear. We expect upward propagation of disturbances arriving at the bottom of the

cavity but we also expect reflection at the top of the cavity (e.g. Schmieder, 1979). Further, the nature of dissipative processes in the chromospheric cavity is not clear. Shock waves are expected to form in the cavity (e.g. Leibacher, 1977; Ulmschneider et al., 1978). The degree to which the chromospheric cavity may propagate disturbances horizontally is also not clear. The result is that we expect a rather chaotic tangle of waves between the temperature minimum and the transition region. The dominance of one type of wave motion at a given location and time in the chromospheric cavity would seem likely to be a matter of local atmospheric structure details (Mein, 1978) and the recent history of mass motions in the surroundings.

There is observational evidence to support all three of the interpretations discussed above and a clear distinction cannot be drawn from our data. We are inclined to favor the last interpretation on the basis that the detailed cross-correlation between the photospheric and the chromospheric fluctuations is quite small. This view is consistent with the irregular geometry of the chromosphere, the relative importance of magnetic fields and the effects these factors have on the nature of wave propagation. We conclude that many of the discrepant results in the literature and our own are not the results of poor observations or interpretation but simply the great complexity of wave propagation above the temperature minimum.

In the future it seems clear that further progress in

understanding wave propagation from the photosphere to the corona will depend on observations which attempt to satisfy several requirements simultaneously: 1. Sufficient spatial resolution to resolve fine structure in the chromosphere. 2. Sufficient range in space and time to resolve the modal structure of trapped waves in the sub-photospheric and chromospheric cavities. 3. High statistical stability by repeated observations in different locations and at different times. 4. An adequate selection of spectrum lines which are easy to interpret and cover the height range between the photosphere and the corona without any gaps in height. This is an extremely formidable observational program which will not be realized soon.

5. Conclusions

Intensity and velocity fluctuations in the photosphere have been compared with intensity fluctuations in the temperature minimum, upper chromosphere, transition region and corona. We find significant fluctuation peaks in the 3-5 mHz range from the photosphere to the upper chromosphere but only a gradual rise in amplitude with decreasing frequency in the transition region and corona. Three different analysis techniques indicate an upward propagation of waves through the photosphere to the temperature minimum. The analyses also indicate upward progression of fluctuations from the upper chromosphere to the corona. The nature of wave propagation between the temperature minimum and the upper chromosphere

is not clear from the analysis. This difficulty is probably due to a change in the acoustic transmission properties of the atmosphere above the temperature minimum complicated by reflections, shock formation, inhomogeneous structure and changes in dissipation processes with increasing height. Single intensity fluctuation events propagating from the photosphere to the transition region cannot be identified unambiguously. In particular, strong intensity pulses in the transition region do not seem to be associated with specific events in the photosphere.

Acknowledgements

We are grateful to Dr. D. Hall for providing the CO observations, to Dr. R. Levine for providing the EUV observations and to Dr. N. Sheeley, Jr. for providing supporting He II and Ca II spectroheliograms. This project was supported by NASA contract NAS8-33104.

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Figure Captions

Fig. 1. Simultaneous observations of intensity fluctuations from the photosphere (525.0 nm) to the corona (Mg X) at the disk center (run 2). The recordings have been smoothed by eye in this illustration. The time duration is 1616 s. The amplitude of the intensity fluctuations is roughly $\pm 1\%$ (Fe I, 525.0 and 523.3 nm), 4% (CO), 15% (H I), 20% (C II), 50% (C III), 40% (O IV), 30% (O VI), 25% (Mg X).

Fig. 2. Amplitude of fluctuations in various spectrum lines as functions of frequency. Dashed lines are velocity fluctuations. (a) Run 1. (b) Run 2.

Fig. 3. An example of a phase difference spectrum showing the phase difference between intensity fluctuations of Lyα and 523.3 nm. Negative phase shift indicates Lyα fluctuations lead 523.3 fluctuations. The cross is used for run 1 and the asterisk for run. 2. The size of the symbols is proportional to the log of the product of the amplitudes of the two fluctuations.

Fig. 4. The normalized cross-correlation between intensity fluctuations of O IV and 523.3 velocity fluctuations (run 2). Zero lag is at the center and a total time lag range of 1616 s is shown. The positive peak indicates that the O IV fluctuations lead the 523.3 fluctuations.

Fig. 5. Summary of time delays of intensity fluctuations

in various lines from Table IV. Brightenings are indicated by dots and darkenings by crosses. a) Phase shift analysis at 3.3 mHz. b) Phase shift analysis at 5.5 mHz. c) Cross-correlation analysis. d) Continuity analysis.

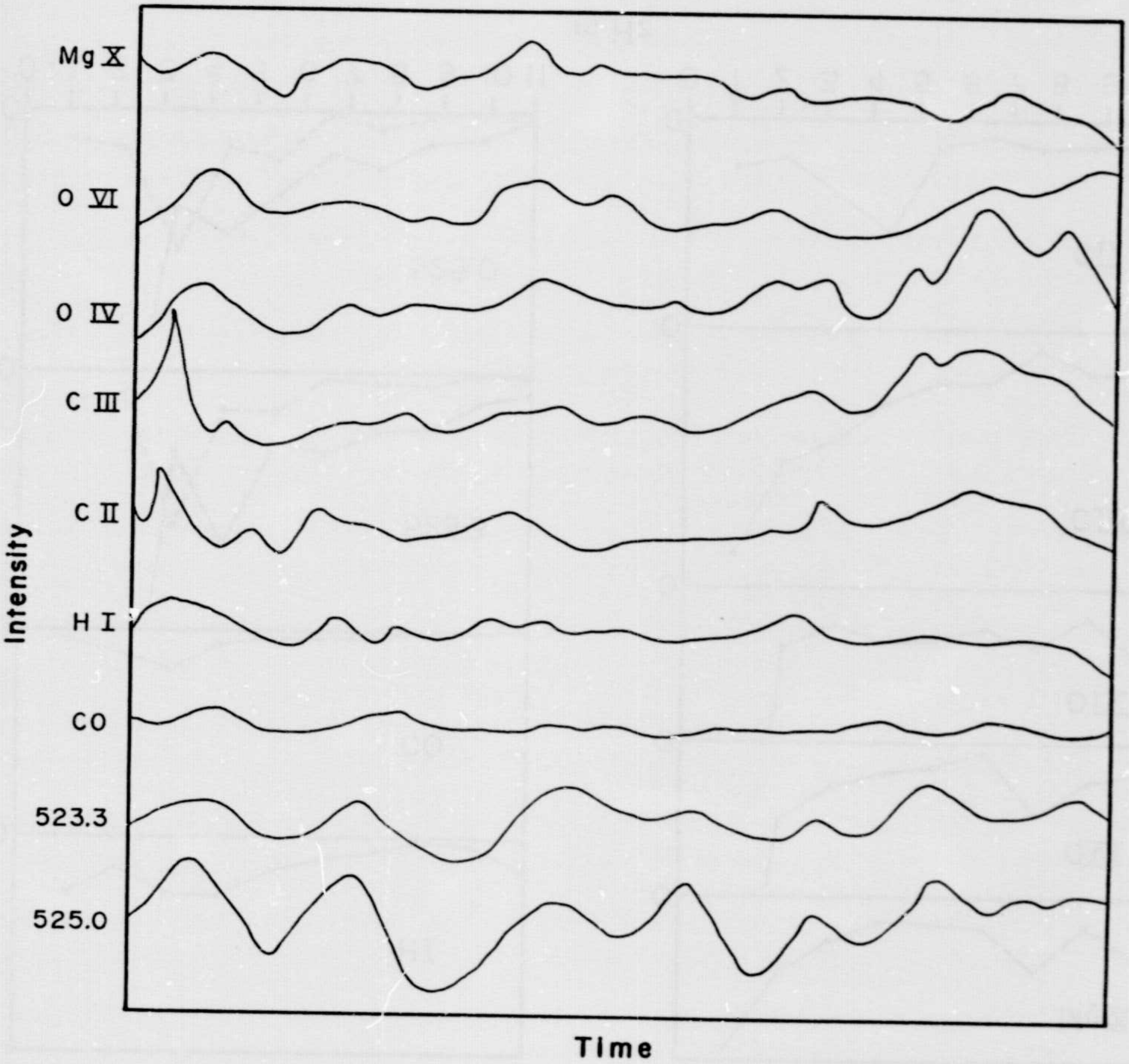
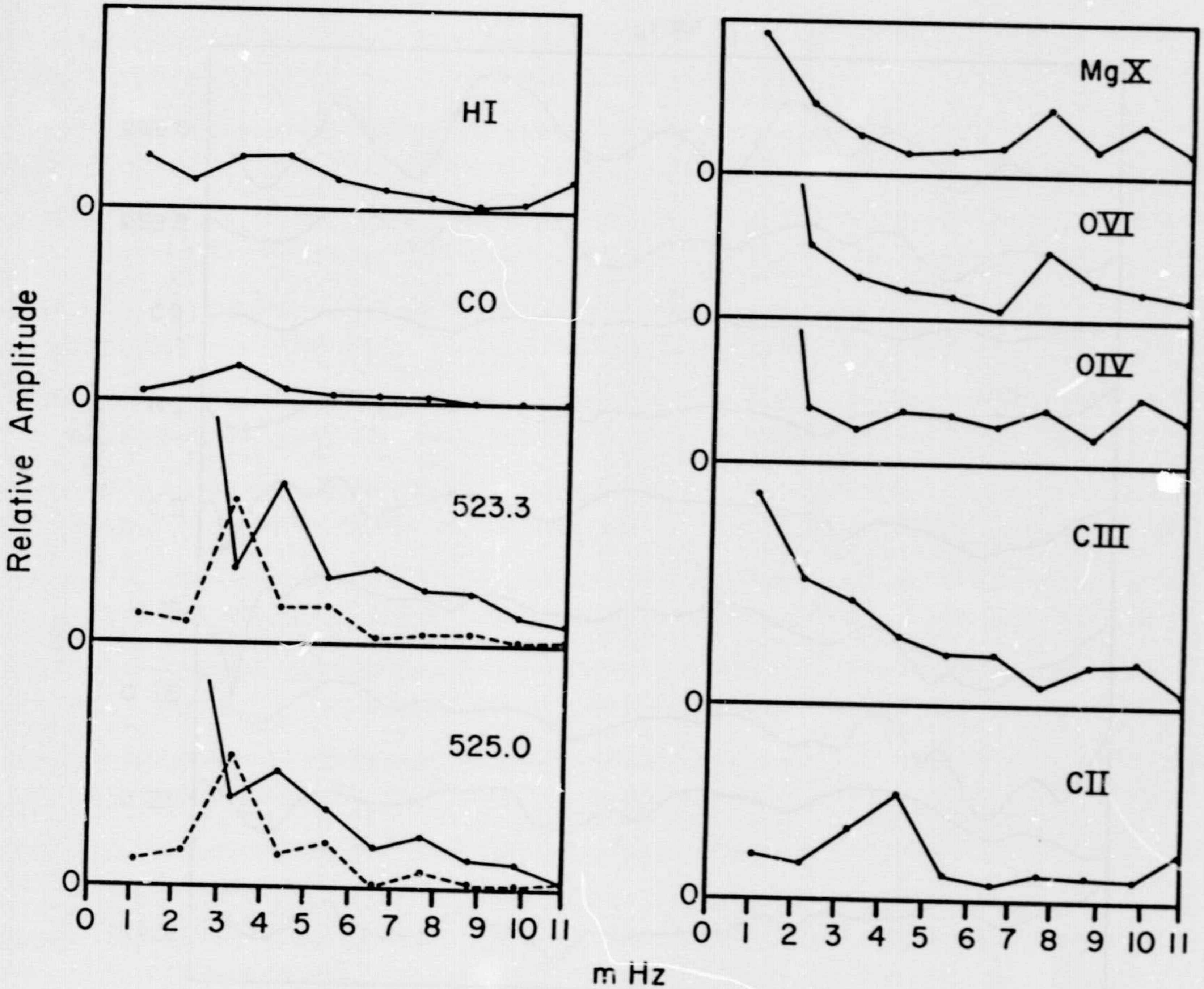
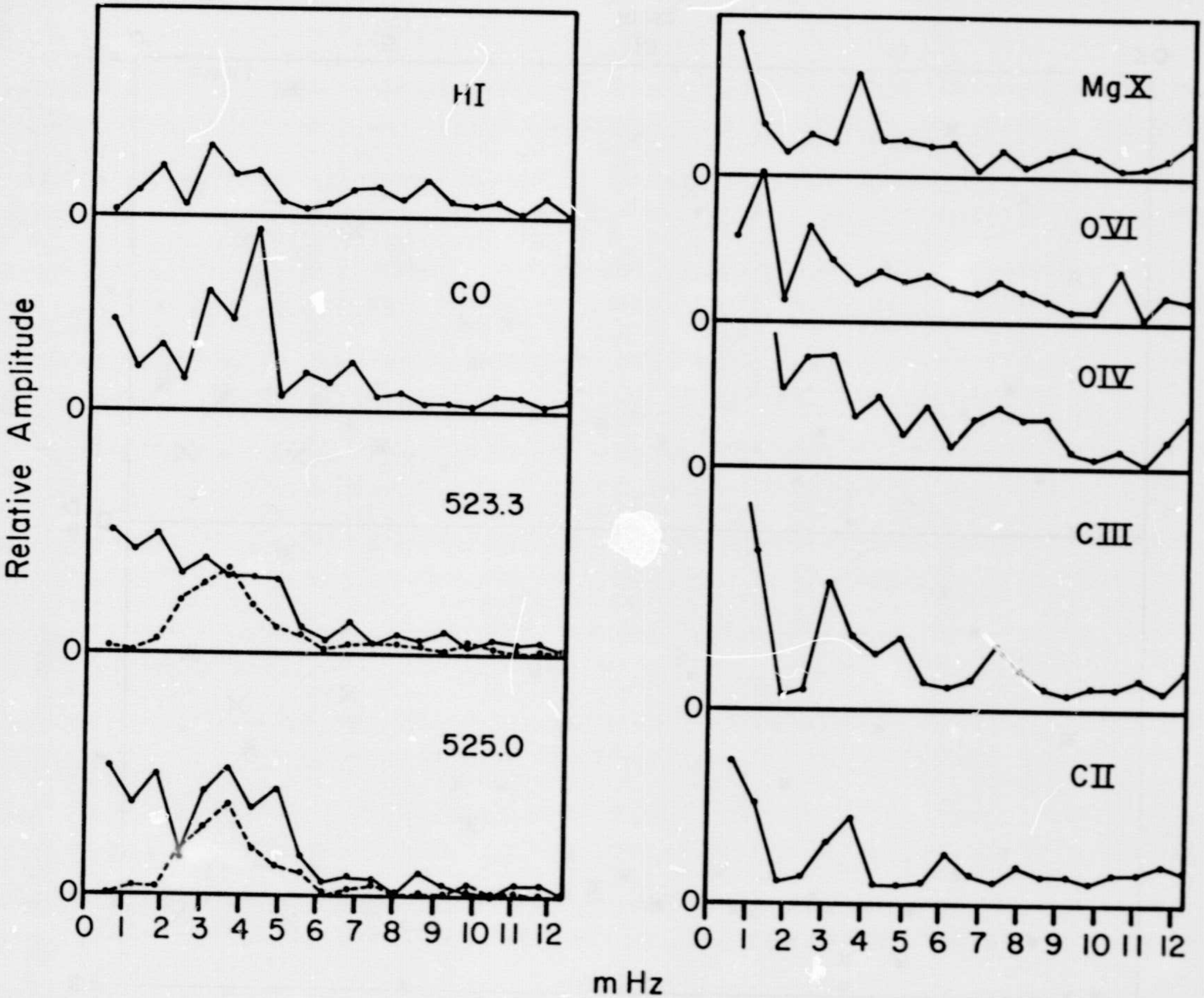


FIGURE 1



Relative Amplitude
HI
CO
523.3
525.0
MgX
OVI
OIV
CIII
CII
0
0 1 2 3 4 5 6 7 8 9 10 11
m Hz

FIGURE 2a



HI
CO
523.3
525.0
Mg X
O VI
O IV
C III
C II
Relative Amplitude
0
0 1 2 3 4 5 6 7 8 9 10 11 12
m Hz

FIGURE 2b

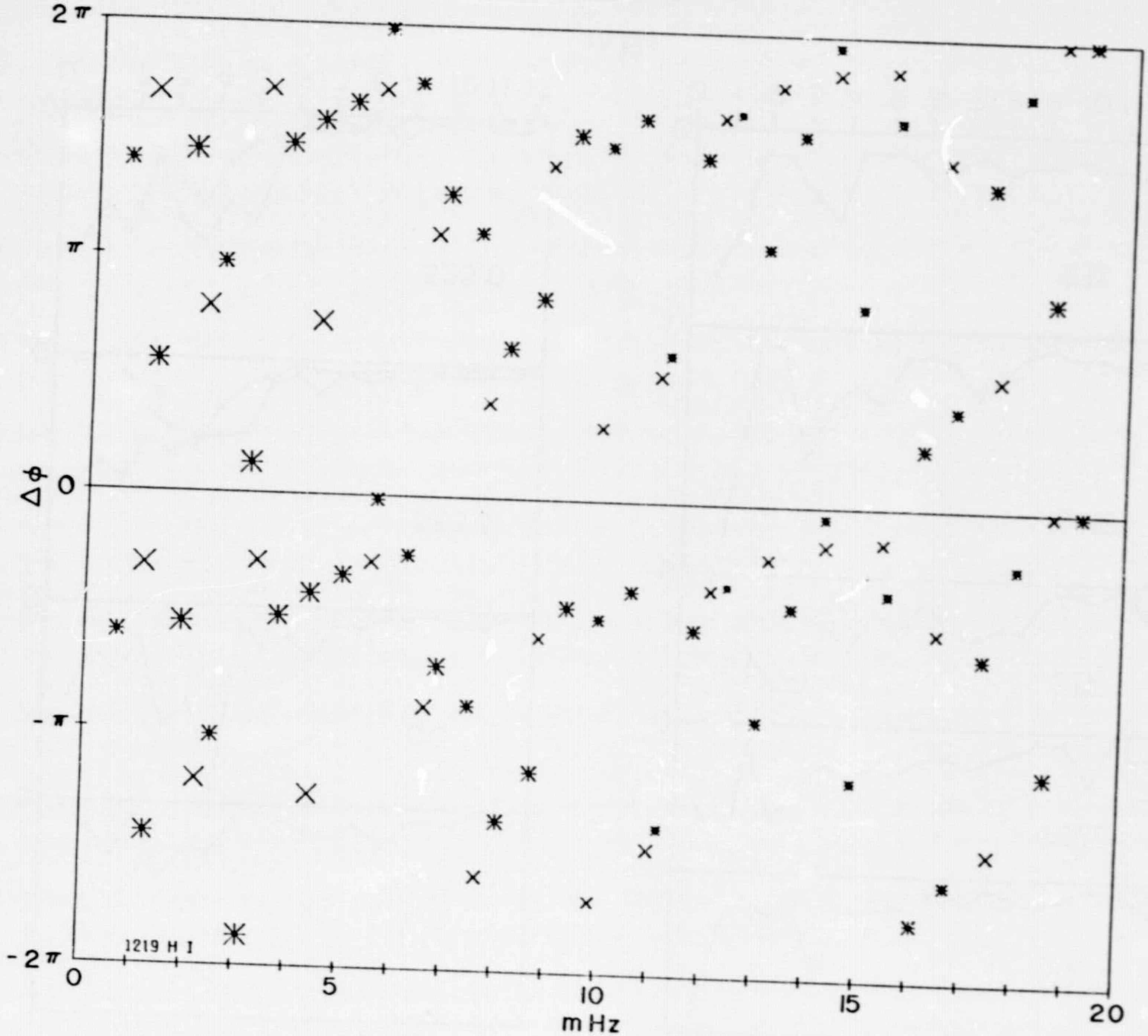


FIGURE 3